Evidence for an Additional Heat Source in the Warm Ionized Medium of Galaxies

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ABSTRACT

Spatial variations of the [S II]/Hα and [N II]/Hα line intensity ratios observed in the gaseous halo of the Milky Way and other galaxies are inconsistent with pure photoionization models. They appear to require a supplemental heating mechanism that increases the electron temperature at low densities n_e. This would imply that in addition to photoionization, which has a heating rate per unit volume proportional to n_e^2, there is another source of heat with a rate per unit volume proportional to a lower power of n_e. One possible mechanism is the dissipation of interstellar plasma turbulence, which according to Minter & Spangler (1997) heats the ionized interstellar medium in the Milky Way at a rate $\sim 1 \times 10^{-25} n_e$ ergs cm^{-3} s^{-1}. If such a source were present, it would dominate over photoionization heating in regions where $n_e \lesssim 0.1$ cm^{-3}, producing the observed increases in the [S II]/Hα and [N II]/Hα intensity ratios at large distances from the galactic midplane, as well as accounting for the constancy of [S II]/[N II], which is not explained by pure photoionization. Other supplemental heating sources, such as magnetic reconnection, cosmic rays, or photoelectric emission from small grains, could also account for these observations, provided they supply to the warm ionized medium $\sim 10^{-5}$ ergs s^{-1} per cm^2 of Galactic disk.

Subject headings: galaxies: ISM — Galaxy: halo — ISM: general — ISM:HII regions

1. Introduction

Although the warm ionized medium (WIM), also called the diffuse ionized gas (DIG), is a principal component of the interstellar medium in our Galaxy and others, the source of its ionization and heating is not understood (e.g., Reynolds 1995; Rand 1998). Observed line intensities,

particularly the high values of [S II]/Hα and [N II]/Hα compared to those in traditional, discrete H II regions surrounding O and early B stars suggest that photoionization by a dilute radiation field plays an important role (e.g., Domgörgen & Mathis 1994); both models and observations indicate that these emission lines originate primarily from warm ($\sim 10^4$ K) regions in which the hydrogen is nearly fully ionized (e.g., Sembach et al 1999; Reynolds et al 1998). It has been suggested by Miller & Cox (1993) and Dove & Shull (1994), for example, that Lyman continuum radiation originating from O stars penetrates the H I cloud layer and ionizes diffuse interstellar gas within the disk and lower halo. While O stars are the only known source with sufficient power to maintain the WIM, the high opacity of the interstellar H I has led others to propose the existence of more widely distributed sources of ionization (e.g., Slavin et al 1993; Mellott et al 1988 and Sciama 1990; Raymond 1992; Skibo & Ramaty 1993).

2. Problems with Pure Photoionization Models

Photoionization models incorporating a low ionization parameter U (the ratio of photon density to gas density) have been generally successful in accounting for the elevated [S II]/Hα and [N II]/Hα and low [O III] λ5007/Hα ratios observed in the WIM (e.g., Domgörgen & Mathis 1994; Greenawalt, Walterbos, & Braun 1997; Martin 1997; Wang, Heckman, & Lehnert 1998). However, the models have failed to explain observed *variations* in some of the ratios. For example, Rand (1998) observed that [S II]/Hα and [N II]/Hα increase with increasing distance |z| from the midplane of NGC 891, having values of 0.2 and 0.35, respectively, near z = 0, and 0.6 and 1.0, respectively, near |z| = 2000 pc. To account for such large ratios at high |z|, Rand had to adopt a hard stellar spectrum (an upper IMF cutoff of 120 $M_\odot$) plus additional hardening as the radiation propagated away from the midplane. However, a hard spectrum appears to be inconsistent with He I λ5876 recombination line observations (Rand 1998, 1997, and references therein).

More significantly, the models fail to account for the fact that, while the variations in [S II]/Hα and [N II]/Hα are large, [S II]/[N II] remains nearly constant. A similar behavior for [S II], [N II], and Hα has been observed in other galaxies (e.g., Golla, Dettmar, & Domgörgen 1996; Otte & Dettmar 1999) as well as in the Milky Way (Haffner, Reynolds, & Tufte 1999). Golla et al (1996) and Rand (1998) have pointed out that the constant value of [S II]/[N II] cannot be reproduced by photoionization models, because in these models variations in [S II]/Hα and [N II]/Hα are primarily the result of variations in the ionization parameter U, which always produce larger changes in [S II]/Hα than in [N II]/Hα. This is due to the different ionization potentials of S and N, with the result that sulfur can be primarily S^+ or primarily S^{++}, depending on the spectrum and strength of the radiation field, whereas nitrogen remains primarily N^+ under nearly all WIM conditions (e.g., Howk & Savage 1999).

Another observation that pure photoionization models fail to reproduce is the rise in [O III]/Hβ with increasing |z|, or increasing [S II]/Hα and [N II]/Hα (Rand 1998, Greenawalt et al 1997). In NGC 891, for example, the [O III]/Hβ intensity ratio more than doubles from 0.3 at z = 0 to about

0.75 a |z| = 2000 pc (Rand 1998). The models predict the opposite trend. Rand proposed an additional source of collisional ionization at high |z| to account for the enhanced [O III] intensity, but emphasized that this would still not explain the constancy of the [S II]/[N II] ratio.

We show that these line ratio variations could be explained by the existence of an additional source of heat in the diffuse ionized gas. In the following sections we use recent emission line data for the Milky Way, obtained with the Wisconsin H-Alpha Mapper (WHAM) spectrometer, to derive the required heating rates and place constraints on possible supplemental heating mechanisms.

3. Line Ratio Variations Due to an Additional Heat Source

3.1. Evidence for Variations in Electron Temperature

Haffner et al (1999) have shown that these emission line observations can be readily explained if the large variations in [N II]/Hα and [S II]/Hα are due primarily to variations in the electron temperature T_e rather than to variations in the ionization parameter U. The constancy of [S II]/[N II] is then a consequence of the fact that the two lines have nearly the same excitation energy. Such temperature variations could also produce increases in [O III]/Hβ, perhaps eliminating the need for a secondary source of ionization. For the Milky Way, Haffner et al (1999) found that an increase in T_e from 7000 K at |z| = 500 pc to approximately 10,000 K at 1500 pc would produce the observed factor of three increases in the [N II]/Hα and [S II]/Hα ratios while keeping [S II]/[N II] constant. Elevated temperatures have also been proposed by Bland-Hawthorn, Freeman, & Quinn (1997) to account for the anomalously high [N II]/Hα in the diffuse gas at the outer edge of the disk of NGC 253. They concluded that the high ratio could not be explained by photoionization alone, but required an additional heat source at large galactic radius that would "selectively heat the electrons without producing a higher ionization state of nitrogen."

These emission line data suggest that the regions with higher [S II]/Hα and [N II]/Hα ratios (i.e., higher temperatures) are regions not just at larger distances |z| from the galactic midplane, but more generally are regions with lower electron density. This is indicated by the strong anticorrelation between these line ratios and the Hα intensity. This anticorrelation is apparent not only in the data showing increasing ratios with increasing |z|, but also in observations at constant |z| (e.g., Rand 1998; Otte & Dettmar 1999; Domgörgen & Dettmar 1997; Golla et al 1996; Ferguson, Wyse, & Gallagher 1996) and at large galactocentric radii (Bland-Hawthorn et al 1997). A strong anticorrelation is also found in the observations of the Milky Way (Haffner 1999; Haffner et al 1999), again, not only with increasing |z|, but also for lines of sight that sample just the relatively low |z| gas in the local Orion arm. Since it is difficult to see how the integration length could affect the temperature, we conclude that variations that are correlated with Hα intensity (i.e., emission measure) are actually variations correlated with density.

If the temperature in fact varies inversely with density in the diffuse ionized gas, then there must

be an additional heat source that dominates over ionization heating at low densities. The heating rate per unit volume from photoionization is limited by recombination and is thus proportional to n_e^2. The cooling rate per unit volume depends upon electron-ion collisions and is also proportional to n_e^2. Therefore, with only photoionization, T_e is nearly independent of n_e (although the density dependence of the ion ratios will have some effect on the equilibrium temperature). However, if an additional heating term were added that was proportional to n_e, or did not depend upon density at all, it would dominate at sufficiently low densities, increasing the equilibrium temperature and producing an inverse relationship between T_e and n_e (Reynolds & Cox 1992). This additional heating term would decouple the heating of the gas from its ionization, driving up the the intensities of [S II] and [N II] relative to Hα while not affecting the ionization states of S and N, i.e., allowing the [S II]/[N II] ratio to remain constant. Such heat sources in the WIM may include, for example, photoelectric heating by dust, the dissipation of interstellar turbulence, and coulomb collisions with cosmic rays, which are proportional to n_e (Draine 1978; Minter & Balser 1997; Skibo, Ramaty, & Purcell 1996), and magnetic field reconnection, which may be nearly independent of density (Gonçalves, Jatenco-Pereira, & Opher 1993).

3.2. Electron Temperature vs |z| in the Perseus Arm

The heating rates due to both photoionization and the supplemental source can be estimated by fitting the predicted variation in [N II]/Hα with temperature to the observed variation in this line ratio. This can be done for the Perseus spiral arm of the Milky Way, where the associated optical emission lines have been kinematically identified and observed to high Galactic latitude with the WHAM spectrometer (Haffner 1999; Haffner et al 1999). As a result, these Perseus arm observations provide both line intensity ratios and electron densities as a function of distance from the Galactic midplane. Figure 1 presents the electron temperatures T_e vs |z| derived from these [N II]/Hα data and the relationship between T_e and [N II]/Hα given by

$$\frac{I_{[\mathrm{NII}]}}{I_{\mathrm{H}\alpha}} = 1.63 \times 10^5 \left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1} \left(\frac{\mathrm{N}}{\mathrm{H}}\right) T_4^{0.426}\, e^{-2.18/T_4}, \tag{1}$$

where T_4 is T_e in units of 10^4 K, N/H is the gas phase abundance of nitrogen, and N^+/H and H^+/H are the fraction of nitrogen and hydrogen, respectively, that is singly ionized. Since $N^+/N \approx H^+/H$ (e.g., Howk & Savage 1999; Haffner et al 1999) and $N/H \simeq 7.5 \times 10^{-5}$ (Meyer, Cardelli, & Sofia 1997), equation (1) can be rewritten simply as

$$\frac{I_{[\mathrm{NII}]}}{I_{\mathrm{H}\alpha}} = 12.2\, T_4^{0.426}\, e^{-2.18/T_4}. \tag{2}$$

Equation (2) and the plot of [N II]/Hα vs Galactic latitude presented in Figure 8 of Haffner et al (1999) were then combined to produce the T_e vs |z| relation for the Perseus arm in Figure 1.

This result covers the Galactic latitude range $-34^{o} \geq b \geq -6^{o}$ averaged over the longitude interval $125^{o} \geq \ell \geq 152^{o}$. The distance to the Perseus arm is assumed to be 2.5 kpc (Reynolds et al 1995, and references therein).

3.3. Electron Density vs |z| in the Perseus Arm

The electron density n_e within the WIM at a distance |z| from the midplane can be derived from the Hα intensity, which is related to the emission measure EM through the relation EM = 2.75 $T_4^{0.9} I_{\mathrm{H}\alpha}$ (from Martin 1988), where EM ($= \int n_e^2$ ds) is in units of cm^{-6} pc and $I_{H\alpha}$ is in rayleighs (1 R = $10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}). Along the line of sight through the Perseus arm, EM can be expressed as $n_e^2 f$L, where L is the path length through the arm, f the fraction of L occupied by ionized hydrogen, and n_e the rms electron density within the ionized regions. Haffner et al (1999) showed that for the same ranges of ℓ and b represented in Figure 1, $I_{\mathrm{H}\alpha}(|\mathrm{z}|) \simeq 5.7\ \mathrm{e}^{-|\mathrm{z}|/500}$ R. Therefore, if L is assumed to have a value of 1000 pc (see Fig. 1 in Becker & Fenkart 1970),

$$n_e(|\mathrm{z}|) = 0.125\, T_4^{0.45} f^{-0.5}\, e^{-|\mathrm{z}|/1000}\ \mathrm{cm}^{-3}. \tag{3}$$

We consider two situations: 1) a constant filling fraction $f = 0.2$ (Reynolds 1991), and 2) a filling fraction that increases with |z| according to the relation given by Kulkarni & Heiles (1987), that is, $f(|\mathrm{z}|) = 0.1\, e^{|\mathrm{z}|/750}$ for |z| < 1740 pc. There is some evidence that f does in fact increase with distance from the midplane (Reynolds 1991); however, the results are sufficiently uncertain that both a constant and varying f are considered here.

3.4. Fits to the T_e vs |z| Relation

We assume that the temperature is determined by a balance between the cooling rate per unit volume (Λn_e^2) in the diffuse ionized gas and two heating rates: the net heating by photoionization, given by $G_0 n_e^2$, plus an additional heating term, given either by $G_1 n_e$ or by just a constant G_2. The heating–cooling balance can then be expressed as either $G_0 + G_1/n_e = \Lambda$, or $G_0 + G_2/n_e^2 = \Lambda$, representing, for example, supplemental heating by turbulent dissipation (G_1), or by magnetic field reconnection (G_2), respectively. Therefore, depending upon the values of G_1 or G_2 relative to G_0, significantly increased heating (relative to photoionization) can occur as the density decreases. This will result in higher equilibrium temperatures at lower densities.

We have adopted the cooling function Λ for low density photoionized gas given in Osterbrock (1989). While this particular cooling function may not be exactly appropriate for the WIM, for T_e > 7000 K (the temperature range considered here) it is a very good approximation, because like the model H II region in Osterbrock, the WIM's cooling function is dominated by [O II] and [N II]. An equilibrium temperature for each value of |z| can be computed from equation (3) and

one of the above heating–cooling balance equations. The values of G_0 and G_1, or G_0 and G_2, can then be adjusted to fit the T_e vs |z| distribution in Figure 1. The best-fit values are listed in Table 1 for four cases: (a) supplemental heating $G_1 n_e$ and constant f; (b) supplemental heating G_2 and constant f; (c) supplemental heating $G_1 n_e$ and a variable $f(|z|)$; and (d) supplemental heating G_2 and variable $f(|z|)$. The associated best-fit curves are also plotted on Figure 1 for comparison with T_e vs |z| inferred from the observed [N II]/Hα ratios in the Perseus arm. Note that the derived values for G_1 and G_2 are proportional to $L^{-\frac{1}{2}}$ and L^{-1}, respectively, where L is the assumed path length through the Perseus arm. Also, Haffner et al (1999) discussed the possible contamination of the [N II] spectra by a weak atmospheric emission line. If this line is present with the intensity of their upper limit (0.1 R), then the best fit values for G_1 and G_2 would be 20% – 30% lower than those presented in Table 1, while G_0 would be less affected.

4. Discussion

Figure 1 shows that all four cases give good fits to the inferred T_e vs |z| distribution, within the uncertainty implied by the jaggedness of the distribution. Therefore, a supplemental heat source with a heating rate per unit volume proportional to n_e^1 or n_e^0 could account for the observed variations in the line intensity ratios. Moreover, these results place tight constraints on the required rates, implying a photoionization heating rate coefficient $G_0 \approx 1 \times 10^{-24}$ ergs cm^{+3} s^{-1}, and a supplemental rate coefficient of either $G_1 \sim 1 \times 10^{-25}$ ergs s^{-1} or $G_2 \sim$ few $\times 10^{-27}$ ergs cm^{-3} s^{-1}. Thus for n_e greater than 1 cm^{-3}, the heating rate per unit volume is dominated by photoionization, while below 0.1 – 0.04 cm^{-3}, the supplemental heating dominates. This value for G_0 corresponds to a stellar ionizing spectrum with $T_{eff} \approx$ 30,000 – 35,000 K (Osterbrock 1989), i.e., late O to early B, and is consistent with the observations of weak He I recombination line emission from the WIM (Tufte 1997, Reynolds & Tufte 1995; Heiles et al 1996).

Values of G_1 near 1 $\times 10^{-25}$ ergs s^{-1} (Table 1) have in fact been predicted for the WIM in the Milky Way by models of photoelectric grain heating (Reynolds & Cox 1992; Draine 1978) and by models of the dissipation of interstellar turbulence (Minter & Spangler 1997). At electron temperatures above 8000 K the net heating by grains decreases sharply due to cooling by electron–grain collisions (Draine 1978), and, therefore, this process is not likely to account for the 9,000 K – 11,000 K temperatures at high |z|, unless photoelectric heating in the WIM is dominated by large molecules (e.g., PAHs) (Lepp & Dalgarno 1988). Minter & Spangler (1997), on the other hand, have predicted an energy dissipation rate of approximately 1 $\times 10^{-25} n_e$ ergs cm^{-3} s^{-1} due to ion–neutral collisional dampening in the Milky Way's nearly fully ionized 10^4 K WIM. They concluded that the dissipation of turbulence probably plays a major role in heating the WIM and contributing to the [S II] and [N II] emission (see also Minter & Balser 1997 and Tufte, Reynolds, & Haffner 1999). Another potential source is coulomb collisions by cosmic rays, which according to some interpretations of the Galactic γ-ray background, could deposit significant power into the interstellar gas (e.g., Skibo et al 1996; Valinia & Marshall 1998).

A heating mechanism that is independent of density (curves b and d in Fig. 1) could also account for these temperature variations. One such mechanism is magnetic field reconnection (Raymond 1992; Birk, Lesch, & Neukirch 1998; Gonçalves et al 1993). A field strength as high as 7 μG (Webber 1998; Heiles 1995) and a time scale of 10^8 yr for the amplification of the field by the Galactic dynamo (Raymond 1992, and references therein) would provide an average power of 6×10^{-28} erg cm^{-3} s^{-1}, a rate that is a factor of 2.5 to 13 below the values for G_2 given in Table 1 —but approximately the rate that is needed, if reconnection occurred only within the more limited volume of the WIM.

5. Summary and Concluding Remarks

The anticorrelation between Hα intensity and the line intensity ratios [N II]/Hα and [S II]/Hα, as well as the constancy of [N II]/[S II] in the diffuse ionized gas of the Milky Way and other galaxies can be explained if the electron temperature T_e increases with decreasing density n_e. An inverse relationship between T_e and n_e would imply that, in addition to photoionization, which heats at a rate proportional to n_e^2, there is an additional source that is proportional to a lower power of n_e.

In the Milky Way the dissipation of interstellar turbulence, with a predicted rate $\sim 1 \times 10^{-25}$ n_e ergs cm^{-3} s^{-1} in the WIM (Minter & Spangler 1998), may be the source of this additional heating, raising the possibility that the observed increases in forbidden line intensities (relative to Hα) in galactic halos is the final step in a turbulent energy cascade that begins with large scale motions of the interstellar gas. However, other mechanisms, such as heating by PAHs, magnetic reconnection, or cosmic rays are also possible provided that within the WIM they have a rate coefficient of the magnitude listed in Table 1.

Measurements of higher T_e in regions with higher [N II]/Hα and [S II]/Hα would provide strong, independent support for the existence of such supplemental heating. These measurements could perhaps be made through accurate observations of the Hα, [N II], and [S II] line widths (e.g., Reynolds 1985), or through observations of other emission lines such as [O II] λ3727 and the extremely faint [N II] λ5755 line, which have higher excitation energies, and thus are more temperature sensitive, than [N II] λ6584 and [S II] λ6716 (see Ferguson et al 1996). We hope to begin some of these investigations in the near future.

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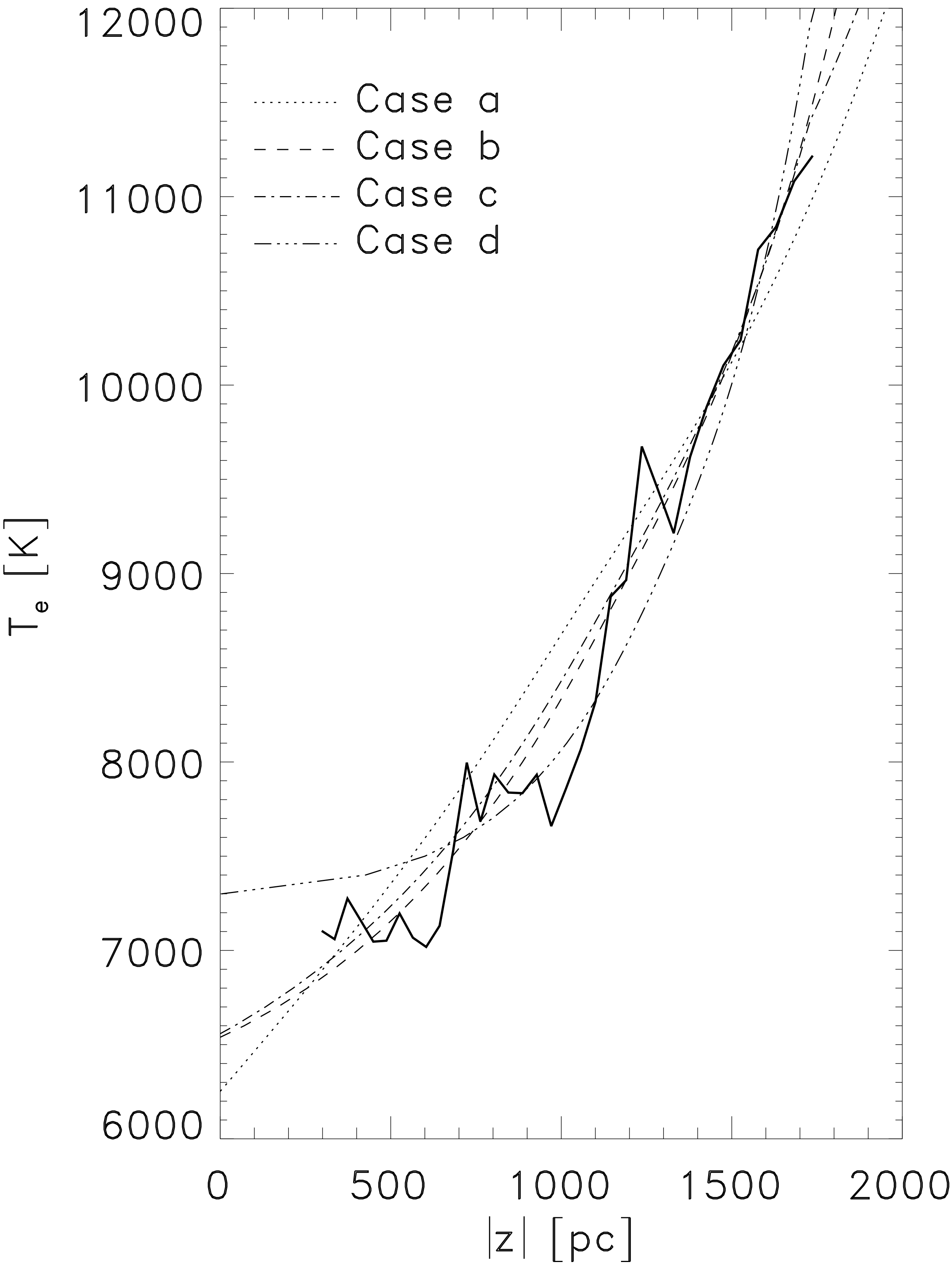
Fig. 1.— Electron temperatures T_e inferred from the [N II]/Hα line intensity ratios plotted vs the distance |z| from the Galactic midplane in the Perseus spiral arm (bold line). Also plotted are the best fits to this T_e vs |z| relation for four cases in which the gas is heated by photoionization plus an additional non-ionizing source (see text).

Table 1. Heating Rate Coefficients for the Perseus Arm

Case	G_0 (10^{-24} ergs cm^{+3} s^{-1})	G_1 (10^{-25} ergs s^{-1})	G_2 (10^{-27} ergs cm^{-3} s^{-1})
a	0.3	1.6	···
b	0.95	···	7.6
c	0.9	0.65	···
d	1.35	···	1.5



12000
11000
10000
9000
8000
7000
6000
T_e [K]
0
500
1000
1500
2000
|z| [pc]
Case a
Case b
Case c
Case d